AIAA 2002-3832

NEXT: NASA's Evolutionary Xenon Thruster

Michael J. Patterson, John E. Foster, Thomas W. Haag, Vincent K Rawlin, and George C. Soulas
National Aeronautics and Space Administration[*]
Glenn Research Center
Cleveland, Ohio

Robert F. Roman
QSS Group, Inc.
Cleveland, Ohio

NASA's Glenn Research Center has been selected to lead development of NASA's Evolutionary Xenon Thruster (NEXT) system. The central feature of the NEXT system is an electric propulsion thruster (EPT) that inherits the knowledge gained through the NSTAR thruster that successfully propelled the Deep Space 1 to asteroid Braille and comet Borrelly, while significantly increasing the thruster power level and making improvements in performance parameters associated with NSTAR. The EPT concept under development has a 40 cm beam diameter, twice the effective area of the Deep-Space 1 thruster, while maintaining a relatively-small volume. It incorporates mechanical features and operating conditions to maximize the design heritage established by the flight NSTAR 30 cm engine, while incorporating new technology where warranted to extend the power and throughput capability.

Introduction

The success of the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) program ion propulsion system on the Deep-Space 1 spacecraft[1] has secured the future for this propulsion technology for other NASA missions. The successful demonstration of the NSTAR ion thruster has provided future mission planners with an off-the-shelf 2.5 kW ion thruster. The 2.5 kW ion propulsion system on Deep-Space 1 performed flawlessly in space operating over 16,000 hours and processing in excess of 70 kg of xenon propellant.

While the NSTAR thruster is appropriate in terms of power level and lifetime for Discovery Class as well as other, smaller NASA missions, its application to large flag-ship type missions such as outer planet explorers and sample return missions is limited due its lack of power and total impulse capability. Several missions under consideration for the Exploration of the Solar System, part of NASA's Space Science Enterprise, have identified a higher power, higher throughput capability, 5/10-kW ion propulsion system as an enabling technology. These missions include the Europa Lander, the Saturn Ring Observer, the Neptune Orbiter, and the Venus Surface Sample Return.[2,3]

At the 15-25 kW power levels and long burn times proposed for these missions the required number of NSTAR thrusters and power processors would prove expensive, complex, large, and heavy to integrate with a spacecraft. Studies for comet and Mars sample return missions as well as outer planet orbiters such as Titan explorer and Neptune orbiter have all shown the need for a higher power, higher total impulse capability thruster to minimize the propulsion system size, mass and complexity. As such a next generation ion propulsion system based on the design successes learned from the NSTAR program is being developed.

A NASA Glenn Research Center (GRC)-led team has recently been awarded a NASA Office of Space Science research project to develop the next generation of ion propulsion system. The successful proposal, for NASA's Evolutionary Xenon Thruster (NEXT), was developed by a team composed of GRC, the Jet Propulsion Laboratory (JPL), General Dynamics Space Propulsion Systems (GD-SPS), Boeing Electron Dynamic Devices (BEDD), Applied Physics Laboratory, University of Michigan and Colorado State University.

NEXT, which is part of the Next Generation Ion Project managed by NASA's Marshall Space Flight Center, Huntsville, Al., will consist of two phases. The first is a demonstration of initial components within one year. The second phase, which NASA may exercise as an option, will last approximately 2.5 years and will advance the system's maturity to NASA Technology Readiness Level (TRL) 5 (component and/or breadboard validation in relevant environment), with significant progress towards TRL 6 (prototype demonstration in relevant environment), achieving a stage of development which the technology can be provided to NASA users to incorporate into planned missions.

The NEXT system will consist of the following:

- A 40-cm diameter electric propulsion thruster (EPT) with a specific impulse of at least 4000 seconds, a specific mass 3.6 kg/kW, efficiencies greater than the NSTAR thruster at all power levels, and a propellant throughput capability required to execute the design reference missions;
- a lightweight, modular power processing unit (PPU) with an efficiency and a specific power equal-to or better-than the NSTAR PPU;
- a highly flexible advanced xenon feed system (AXFS) which uses proportional valves and thermal throttles to significantly reduce mass and volume relative to the NSTAR feed system; and
- a simple, lightweight EPT gimbal.

Validation of NEXT will dramatically advance state-of-the-art ion propulsion technology, with significant gains in EPT capability, as enumerated in Table I.

Table I – EPT Attribute Comparison

Engine Attribute	NSTAR	NEXT
Max. Input Power, kW	2.3	Up to 8
Throttle Range	4:1	Up to 8:1
Max. Specific Impulse, S	3,170	4,050
Efficiency @ Full Power	62%	68%
Propellant Throughput, kg	83 design, 140 demo	>300
Specific Mass, kg/kW	3.6	3.6

The NEXT thruster approach leverages the investments made at GRC in fiscal year 2001 for the development of a next generation engine.[4,5] During this time, design analyses were performed, throttling tables were defined, two engine concepts were developed, and laboratory model (LM) engines were fabricated.[5] The design of the discharge chamber magnetic circuit, magnet retention scheme, and flake-containment approach was completed, and multiple 40-cm diameter ion optics and discharge cathode assemblies were fabricated.

Preliminary performance characterizations of a 40-cm LM engine were conducted for input power levels ranging from about 1.1 kW to 7.3 kW.[5] The efficiency at 7.3 kW was approximately 68% at 3,620 seconds specific impulse. Ion optics performance (perveance and electron backstreaming; beam divergence and beam current density profiles) was documented, as were temperatures of critical components, including the discharge cathode and magnets. The 40-cm ion optics performance was comparable to the 30-cm NSTAR flight ion optics.[6] Test data show that discharge cathode and magnet temperatures for the 40-cm engine are within design limits and provide significant design margin up to at least 10 kW.

This paper discusses the activities to develop the NEXT thruster to engineering model (EM) and prototype model (PM) levels.

Thruster Design

Beginning in 1999, GRC evaluated the possibility of extending the NSTAR 30-cm thruster power and specific impulse envelope. Short-duration tests of 30-cm NSTAR thrusters were conducted at power levels at and above 5 kW, at specific impulse levels as high as 5,600 seconds.[7-9] It was concluded that a modest increase in thruster input power could be achieved with improvements in ion optics and magnet technology.

However, based on thermal, current density, and electric field strength limitations, significant increases in 30-cm thruster input power beyond about 3.5 kW appear impractical and high risk in terms of lifetime. This is a consequence of the modest thruster beam diameter. Additionally, the NSTAR non-ferrous discharge chamber, which was dictated by weight considerations, results in a peaked current density profile and degraded ion optics performance. Another consideration is that further 30-cm thruster investment by the government may duplicate US industrial efforts (e.g., Boeing's 25-cm thruster) rather than advance the state-of-the-art.

From these activities, an NSTAR-derivative engine with 40 cm beam diameter was selected. An engine of this size has twice the beam area of the NSTAR 30 cm (28 cm beam diameter) thruster. Doubling the beam area allows operation at significantly higher power while maintaining low voltages and current densities. Thus, potential complications associated with high-voltage electrode operations are avoided. At an input power of 4.7 kW, the engine would be operating at approximately the same operating voltages and beam current density as the 2.3 kW

NSTAR thruster, and hence would be expected to yield the same operating lifetime, but producing twice the thrust.

The NSTAR thruster has demonstrated >180 kg propellant throughput in ground testing, which is substantially higher than the original design goal of 83 kg. A greater than 2 times increase in throughput capability for the 40-cm engine is anticipated (based on a 2 times increase in beam area, an improved flatness parameter, and an associated reduction in local charge exchange production[4]) which is sufficient to meet mission requirements. The engine capability is expected to reach >300-kg by virtue of an advanced, molybdenum ion optics design that includes an accelerator electrode that is thicker than that of NSTAR.[6] This is beyond the 'single-engine-out' requirement for proposed Neptune and Saturn missions.

The NEXT 40-cm engine incorporates design improvements beyond NSTAR. These improvements include:

- A ferrous discharge chamber for improved beam flatness and reduced discharge losses
- High-temperature stabilized rare-Earth magnets
- A compact propellant isolator
- Advanced ion optics design for longer life

The mechanical integrity and design maturity of the 40-cm EM engine at the completion of the project first phase is expected to be superior to that of the engineering model of the NSTAR thruster (also manufactured by GRC) because it is being designed for the anticipated vibration environment.

Mild steel is used in the construction of the discharge chambers for the 40 cm LM and EM engine designs fabricated at NASA GRC. Both 40 cm engine designs use ring-cusp magnetic circuits, with high-field strength permanent magnets for plasma containment.[10] A flake-retention scheme is employed in the discharge chamber, which also acts as a magnet retainer. The material, preparation, and installation processes employed for the flake-retention system are identical to those implemented on the NSTAR 30 cm thruster. Both LM and EM 40 cm engines also incorporate a reverse-feed propellant injection process for the main plenum.

The discharge cathode assembly for the 40 cm engine is scaled from the NSTAR 0.64 mm diameter hollow cathode to accommodate the estimated emission current range, and uses similar design and manufacturing processes. The neutralizer is an enclosed-keeper hollow cathode. Internal dimensions are adjusted to accommodate the higher emission current requirements for the 40 cm engine, and do so at reduced ratios of propellant flow rate-to-emission current, relative to the NSTAR neutralizer cathode.

Two design approaches are being pursued for the 40 cm ion optics. These include: NSTAR-type electrodes of increased beam diameter, and thicker accelerator-electrode geometry. Both are two-grid designs constructed of molybdenum. The electrode mounting system is scaled from the NSTAR design and also uses the same materials as that implemented in the 30 cm thruster. Figures 1a-c show front, isometric, and side perspectives of the 40 cm EM version of the engine, respectively.

Figure 1a - Front perspective, EM 40 cm engine; neutralizer at 12-o'clock position.

Figure 1b - Isometric, 40 cm EM engine.

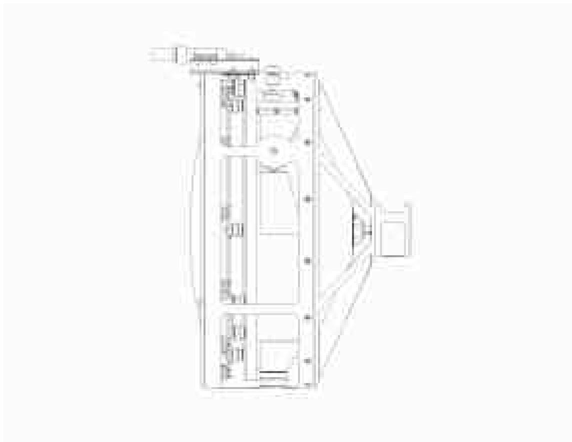

Figure 1c - Side perspective, 40 cm EM engine.

Thruster Manufacturing and Performance Evaluation

NEXT's 40-cm engine will leverage the manufacturing processes of the GRC NSTAR ion thruster. Heritage from NSTAR includes critical processes used in subassemblies, such as the spun-form chamber components; cathode heaters and components; ion optics; propellant isolators; flake-containment mesh; and electrical wiring. The continuity between NSTAR and NEXT is intended to minimize the set of unknowns associated with a new mechanical design and maximizes the value of previous investments in ion engine technology.

GRC will manufacture, assemble, and conduct performance and life tests of EM engines in Phase 1 of the program. The first EM engine will undergo performance evaluations, followed by a sine vibration test, and a 2000-hour, high-power wear test. The sine sweep resonance search on the EM engine will identify possible weaknesses in structure and the results of the test will be incorporated into the PM engine design, to be manufactured in Phase 2.

Two additional EM engines will be assembled during Phase 1 (units 2 and 3). Unit 2 will be performance characterized over the full performance envelope, and then tested in the Phase 1 single-string system demonstration with the breadboard PPU and AXFS. Unit 3 will be assembled in Phase 1; assembly knowledge will be transferred to the PM engine contractor (GD-SPS) by virtue of their participation. As a backup, this engine will be available to mitigate schedule and technical risk issues. During Phase 2, Unit 2 will be used for an engine-level, radiated electro-magnetic interference (EMI) test and subjected to a long-duration wear test.

Under the planned NEXT Integrated Product Team (IPT) approach, GD-SPS will lead the Phase 2 engine design and manufacturing process. This will harness the best engineering expertise in engine development at GD-SPS, BEDD, JPL, and GRC.

GD-SPS–which will design and assemble 2 PM engines in Phase 2–brings to the NEXT team their proven capability in Design for Manufacturing and Assembly (DFMA) which reduces component count, eases assembly, reduces cost, and improves the structural integrity of the engine. These techniques were previously employed in the manufacturing of a simplified 30-cm EM engine that demonstrated performance comparable to that of NSTAR EM and flight engines.[11]

GD-SPS will manufacture the ion optics—which will be evaluated in component and engine testing in their facility and at GRC—using GRC's hydroforming rig. This rig plays a key role in a unique process developed by GRC for forming the dome shape of the ion optics while maintaining the aperture alignment required for beam extraction. It was used to fabricate the optics for the DS1 engine, and 40-cm diameter EM ion optics.

During Phase 2, both PM engines will undergo detailed performance evaluations, with one engine submitted to a full vibration test. The other engine will be subjected to additional performance tests (including thermal vacuum, gimbal integration, vibration with gimbal, and brass board PPU integration) and will then be used in the single-string EM system demonstration. Both PM engines will perform in a multi-engine system demonstration with the EM AXFS.

Performance assessments will evaluate engine operation over its design input power throttling and specific impulse ranges. They will also provide information for service life and thermal modeling. Performance assessments will be conducted on all EM and PM engines in Phases 1 and 2. These will include component (i.e. discharge chamber, neutralizer, and ion optics performance) and engine performance.

The following beam parameters will also be documented:

- Beam flatness for grid service life modeling
- Beam divergence to determine thrust losses
- Beam plasma potentials for spacecraft interactions modeling
- Doubly-to-singly-charged ion current measurements to determine thrust losses
- Thrust vector stability

The selection criterion for the facilities proposed for engine performance assessments is to establish the highest-fidelity simulation required for each specific test to yield transportable results. For wear test evaluations of the engine, GRC's VF5 and VF6, the highest pumping speed and largest electric propulsion vacuum facilities in the country, will be used.

Thruster Life Testing and Assessment

The NEXT 40-cm engine life capability will be validated through a combination of high-power wear tests and modeling. Previous ion engine wear tests revealed unanticipated wear mechanisms.[12-14] Experimental evaluations form the backbone of the NEXT validation process and are essential to life demonstration. The wear tests, in situ diagnostics, and real-time diagnostics will yield reliable life data with minimal time expenditure and cost. The lifetime modeling efforts will be implemented to reduce the experimental workload and enhancing the confidence in the design life. A list of key life-limiting issues is given in Table II, along with the techniques to be employed in the life assessment.

The life assessment analyses in Phase 1 will include results from a 2000-hour, high-power wear test of an EM engine and component life models. JPL, Colorado State University, and the University of Michigan will also perform independent analyses of 40-cm engine life capability. The conclusion of the Phase 1 efforts will be a high-confidence life assessment of the proposed engine design.

Table II – EPT Life-Limiting Issues

Component	Life-Limiting Phenomenon	Technique
Discharge and Neutralizer Cathodes	• Depletion of low-work function material • Keeper and cathode erosion leads to structural failure • Keeper shorts to the cathode	• Wear tests • Component level tests • Real-time diagnostics • Plasma model • Insert Chemistry model • Probabilistic Failure Analysis (PFA)
Accel Grid	• Aperture enlargement leads to electron backstreaming • Structural failure due to erosion • Accel and screen grid short together	• Wear Tests • Real-time diagnostics • *In situ* diagnostics • Plasma model • PFA
Screen Grid	• Removal of web leads to: direct impingement on the accel grid, and structural failure	• Wear Tests • Real-time diagnostics • Plasma model • PFA
Propellant Isolators	• Increasing leakage current with time	• Wear tests • Component level tests

In Phase 2, the design of the engine will be modified as warranted by results of the Phase 1 life assessment. A wear test of an EM engine will then demonstrate at least 300 kg xenon throughput at high power, and provide data for benchmarking the models. Phase 2 service life modeling efforts will also include consideration of the effect of the modified charge-exchange environment created by clustering the engines. By the end of Phase 2, the NEXT engine will have demonstrated a propellant throughput capability that meets the next generation spacecraft requirements.

Thruster Development Status

Fabrication of LM 40 cm engines has been completed, and detailed performance characterizations are on-going at NASA GRC. An EM 40-cm engine design (see Figure 1) based on the most promising LM concept has been assembled and is also under test. The design of several components for the EM engine—including the spun-formed, partial-conic discharge chamber, hollow-cathodes, and ion optical system—are derived from NSTAR engine technology.

Table III provides performance data for the LM version of the 40 cm engine operating on xenon propellant for a power range from about 1.1 to 6.9 kW, where V_{bps} is the beam power supply voltage. As indicated, the specific impulse and efficiency varies from about 4060 seconds and 0.69 at 6.9 kW, down to about 2300 seconds and 0.51 at 1.1 kW.

Table III – EPT Performance

V, V_{bps}	F, mN	I_{sp}, sec	P_{in}, kW	Eff.
5.92 mg/sec				

1800	238	4060	6.90	0.69
1570	222	3750	6.06	0.67
1400	211	3570	5.50	0.67
1180	192	3255	4.70	0.65
4.65 mg/sec				
1800	182	3950	5.29	0.67
1570	170	3690	4.67	0.66
1400	160	3480	4.21	0.65
1180	148	3200	3.64	0.64
1020	137	2970	3.21	0.62
3.43 mg/sec				
1800	135	3970	3.98	0.66
1570	126	3700	3.51	0.65
1400	119	3490	3.17	0.64
1180	109	3200	2.74	0.63
1020	102	2980	2.43	0.61
2.17 mg/sec				
1800	81.4	3770	2.44	0.62
1570	75.7	3510	2.15	0.60
1400	71.5	3310	1.95	0.60
1180	65.7	3040	1.69	0.59
680	49.6	2300	1.11	0.51

Development status of the ion optics may be found in a companion publication.[15]

Concluding Remarks

NASA's Glenn Research Center has been selected to lead development of NASA's Evolutionary Xenon Thruster system, as follow-on to the highly-successful Deep-Space 1 system. The system is envisioned to incorporate a lightweight 40-cm diameter electric propulsion thruster, a lightweight, modular power processing unit, a lightweight, low-volume, highly flexible advanced xenon feed system, and a simple, lightweight gimbal. During this two-phase program, the thruster will be developed to prototype model, with manufacturing of this unit conducted by General Dynamics Space Propulsion Systems. General Dynamics will also manufacture the AXFS. Boeing Electron Dynamic Devices will manufacture the PPU.

To date, fabrication of laboratory model 40 cm engines has been completed at GRC, and detailed performance characterizations are on-going at NASA. An engineering model 40-cm engine design has been assembled at GRC and is also under test. Typical engine performance at 6.9 kW is 4060 seconds specific impulse, 238 mN thrust, and 69% efficiency.

References

[1]Polk, J.E., et al., "Validation of the NSTAR Ion Propulsion System On the Deep Space One Mission: Overview and Initial Results," AIAA Paper No. 99-2274, June 1999.

[2]Gershman, R., Manager, Planetary Advanced Missions, JPL, "ESS Technology Requirements," dated June 18, 1999.

[3]Anon., Integrated In-Space Transportation Planning, Summary of Process and Technology Prioritization, May 2001.

[4]Patterson, M.J., et al., "Ion Propulsion Development Activities at the NASA Glenn Research Center," IEPC Paper No. 01-088, October 2001.

[5]Patterson, M.J., et al., "Next-Generation 5/10 kW Ion Propulsion Development Status," IEPC Paper No. 01-089, October 2001.

[6]Soulas, G.C., "Design and Performance of 40 cm Ion Optics," IEPC Paper No. 01-090, October 2001.

[7]Sarver-Verhey, T.R., Domonkos, M.T., and Patterson, M.J., "Thermal Characterization of a NASA 30-cm Ion Thruster Operated up to 5 kW," AIAA Paper No. 2000-3816, July 2000.

[8]Patterson, M.J., et al., "Ion Propulsion Development Activities at NASA Glenn Research Center," AIAA Paper No. 2000-3810, July 2000.

[9]Rawlin, V.K., et al., "High Specific Impulse, High Power Ion Engine Operation," AIAA Paper No. 2002-3838, July 2002.

[10]Sovey, J.S., "Improved Ion Containment Using a Ring-Cusp Ion Thruster," *Journal of Spacecraft and Rockets*, Vol. 21, Sept.-Oct. 1984, pp. 488-495.

[11]King, D., et al., "Design for Manufacturing Improvements and Demonstration of a 30 cm Ion Thruster," AIAA Paper No. 2000-3271, July 2000.

[12]Pawlik, E.K. and Reader, P.D., "Accelerator Grid Durability Tests of Mercury Electron-Bombardment Ion Thrusters," NASA Technical Note D-4054, July 1967.

[13]Patterson, M.J. and Sarver-Verhey, T.R., "5-kW Xenon Ion Thruster Lifetest," AIAA Paper No. 90-2543, July 1990.

[14]Patterson, M.J., et al., "2.3 kW Ion Thruster Wear Test," AIAA Paper No. 95-2516, July 1995.

[15]Soulas, G.C., "Performance Evaluation of 40 cm Ion Optics," AIAA Paper No. 2002-3834, July 2002.